Balanced and unbalanced networks in offshore wind farms

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1 INTRODUCTION

The cable routing problem in offshore wind farms consists in designing a transportation network to transfer the electricity generated by wind turbines to a central hub (substation) which is connected to shore. The submarine electrical cables are expensive, comprising about 5% of the total capital expenditure (CAPEX) of an offshore wind farm (BVG Associates, 2019). For this reason, the optimization of cable routing has been investigated in literature, with the objective of finding the cable routing of minimum cost (Bauer & Lysgaard, 2015).

One important constraint for the cable routing problem is that cable crossings are forbidden, due to the increased installation costs and difficult maintenance. Another constraint is that the routing must avoid all obstacles in the wind farm sea area. These obstacles may be due to unsuitable seabed conditions, to ship wrecks, and to regulations, such as fishing corridors and natural reserves. Cables must not cross any of these areas for the routing solution to be feasible.

A cable routing allows only one electrical cable to exit from each turbine, and multiple cables to enter turbines and the substation. Each sub-tree leaving the substation is denoted a *root-branch*. A property of cable routing solution is related to how many turbines are present in each root-branch. If the number of turbines in each root-branch is the same or differs at most by one, we denote the solution *balanced*.

While literature mainly has focused on the general *unbalanced* cable routing problem, in industry the wind farm developers favor balanced cable routing solutions. As the solutions to the balanced problem are a subset of the solutions to the unbalanced formulation, unbalanced solutions may be cheaper than balanced. The drawbacks of the unbalanced routing are related to the additional electrical equipment cost that needs to be installed in the offshore substation. In particular, the cost of installing a spare Offshore Transformer Module (OTM) on the substation is about 5M€ (Walling & Ruddy, 2005), depending on its rating. In the case of a balanced cable routing, a single type of transformer is needed as spare in case of failures (online spare), since the transformer share the same electrical loads and can substitute any of the transformers in case of failure. For the unbalanced case instead, different transformer ratings and different spares would be needed, making this option less attractive in the industry.

The contributions of this work are:

- We develop a matheuristic that uses different neighborhoods to optimize the cable routing problem, for both balanced and unbalanced networks.
- We present a technique to handle obstacles in the cable routing based on a visibility graph.
- We quantify the difference between balanced and unbalanced cable routing on a set of realistic wind farm instances, taking into account the additional OTM costs.

2 METHODOLOGY

We use a matheuristic to solve the cable routing problem for both the balanced and the unbalanced cases. The technique is based on the work of Cazzaro & Pisinger (Submitted 2021). As a first pre-processing step, we compute and store all the shortest paths using a so-called visibility graph in order to avoid obstacles. Then we use a technique called *Sweep* to generate an initial solution without crossings. Finally, we use a Large Neighborhood Search (LNS) to improve the cable routing, using a mix of heuristic and exact methods. We outline in the following sections an approach to deal with obstacles in the wind farm, the strategies used in the heuristic, and the changes needed to consider the two network designs.

2.1 Obstacles

Let V be the nodes of turbines and of the substation in the wind farm that we want to connect with electrical cables to transport the generated electricity. There are $O(V^2)$ possible connections to be used in the network.

Due to obstacles, some of these direct connections will cross the obstacles in the wind farm, and thus cannot be used. We are interested in computing the shortest paths from each node to every other node by routing each connection around obstacles. To this end, we use a visibility graph, similarly to Yi *et al.* (2019). A visibility graph contains only edges that have *visible* nodes, meaning that two nodes have a direct connection that does not cross any obstacle. We first add to the visibility graph all the nodes of V plus all the nodes that define obstacles (as polygons). Then, we use the Dijkstra algorithm to compute the shortest paths from each node to all others. The Dijkstra algorithm is called V times, and we store V^2 shortest paths in an ad-hoc data structure. The advantage of this procedure is threefold. First, it can be computed in a pre-processing step, so it does not impact the subsequent optimization time. Second, it allows us to consider the whole solution space of the problem and possibly reach better solutions. Third, it can be adopted by existing optimization techniques that do not include obstacles with minimal overhead.

2.2 Initial solution

We use a *Sweep* algorithm to generate an initial solution without cable crossings. The idea of Sweep takes inspiration from Gillett & Miller (1974), which used it for the Vehicle Routing Problem. In Sweep, we divide the turbines in groups, that are then connected together with the substation. These groups are formed by considering the angle that turbines form with the substation. The turbines are thus partitioned in sectors around the substation, making it unlikely that crossings are generated between different groups. Thanks to the visibility graph, obstacles are accounted for when forming groups. The Minimum Spanning Tree is then computed for each group, using the Prim-Dijkstra algorithm, so that the turbines are connected together with the substation. For the balanced case, the groups will be formed with the same amount of turbines, while for the unbalanced case a wider set of partitions can be considered. In our implementation, the Sweep is implemented as a multi-start procedure: we try many different partitions and keep the one with lowest cost.

2.3 Matheuristic

After the Sweep procedure, we use Large Neighborhood Search (LNS) to improve the solution. The method operates on neighborhoods of increasing complexity and uses both heuristic and exact methods to repair solutions.

- *Swap*: this method exchanges two turbines between a pair of root-branches to improve the cable routing. After the move, we recompute the Minimum Spanning Tree to connect the turbines in each group and we re-evaluate the solution. If the cost improves, we move to the new solution, otherwise we revert the root-branches to the original configuration and continue the search. For the balanced network, the Swap move is symmetric to preserve the number of turbines in each root-branch. For the unbalanced network, instead, we can consider an additional move: a single turbine can move from its own branch to another.

- *Double Swap*: we extend the Swap move by considering two moves at a time, before re-evaluating the solution. In this way, we allow a temporary worsening of the solution in the first move to reach a better solution with the second swap. In addition, we can perform the Double Swap between two branches but also among three of them, which helps to improve the solution.

- *Cycle Swap*: we use a MIP formulation to allow the exchange of turbines between several branches at a time, in particular for the balanced case. We compute a move matrix and an associated cost vector for each turbine. This vector estimates the cost of moving a turbine to its best improvement in a nearby branch. Each turbine leaving a branch needs to be replaced by another one to maintain a balanced solution: this makes the formulation of the move matrix totally unimodular, which can be solved efficiently with a LP solver.

- *Re-partition*: we use a MIP formulation of the cable routing problem to improve the solution. Differently from usual exact approaches in literature, we do not solve the whole cable routing problem but only a subset, limited to two branches at a time. In this way, the MIP model is small and can be solved to optimality in a short time. For the balanced case, we add the balancing constraint to the MIP, which is omitted for the unbalanced network.

All different neighborhoods explored in the LNS contribute to improving the initial solution obtained with the Sweep heuristic. For more details on the LNS heuristic, we refer to Cazzaro & Pisinger (Submitted 2021).

3 RESULTS AND DISCUSSION

We compare the two network designs on a set of *synthetic instances* published in Cazzaro & Pisinger (2022). These 10 instances have a high number of turbines to connect together and many obstacles in the area, as in real wind farms. We assume a set of two cables is available to connect the turbines, based on Das & Cutululis (2017). The first cable costs 240€/m and can support 6 turbines (of 10MW capacity), while the second cable costs 336€/m and can support 8 turbines. As mentioned in the first section, the total cost of an additional OTM is about 5M€, including installation (Walling & Ruddy (2005)).

We quantify the difference of costs between the balanced cable routing and the unbalanced case, taking into account the cost due to one additional OTM. We report the results of the two cable routing networks in Table 1.

Considering the cable costs alone, the unbalanced network reaches lower cost solutions in all the tested instances. When we add the cost of an extra OTM, though, the situation is reversed: because of the reduced installation costs, the balanced case is strongly preferable. Indeed, this is

Table 1 – *Comparison of cable routing costs for balanced and unbalanced networks on the synthetic instances. The cheaper the better.*

Instance	Unbalanced (M€)	Unbalanced + OTM (M€)	Balanced (M€)	Delta (M€)	Delta (%)
A	20.79	25.79	21.62	4.17	16.17
B	54.08	59.08	54.74	4.34	7.35
C	51.83	56.83	53.49	3.34	5.88
D	96.07	101.07	97.14	3.93	3.89
E	71.98	76.98	74.36	2.62	3.40
F	94.09	99.09	95.43	3.66	3.69
G	75.41	80.41	78.15	2.26	2.81
H	114.1	119.10	117.41	1.69	1.42
I	202.51	207.51	205.9	1.61	0.78
J	127.2	132.20	130.02	2.18	1.65

due to the relatively low savings between the two network designs, which are not large enough to offset the additional electrical components. This is the main reason why the balanced network is preferred by wind farm developers, and also a motivation to further study this network option. Even if the cost of an OTM was reduced to 3 M€ instead of 5 M€, all but instances I and J would still be more economic when using a balanced routing.

4 CONCLUSIONS

In the presented work, we quantified the cost difference between two networks: the balanced and the unbalanced cable routing. In addition, the visibility graph technique we proposed can be applied in general to routing problems with obstacles. As an example, we generalized the well-known Sweep algorithm to operate on visibility graphs, which can be used in any transportation problem with obstacles. Advanced matheuristic using neighborhoods of increasing complexity shows very promising results. In Cazzaro & Pisinger (Submitted 2021) it has been shown that it is on average only 0.01% more expensive than MIP solutions. The matheuristic can easily be generalized to Hamiltonian-cycle branches. Finally, developed methods are applicable to any kind of transportation problems where the individual strings leaving the hub must be balanced.

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